Dynamical Studies in Hurricane Intensity Change and Hurricane Motion

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LONG-TERM GOALS/OBJECTIVES

The long-term goals and objectives of this research are to develop a physical understanding of tropical cyclone (TC) intensity change processes and the motion of a three-dimensional hurricane vortex. Towards these goals, this year's work focused on four areas: barotropic hurricane motion, assessing the traditional balance approximation for the asymmetric flow in hurricanes, understanding the impact of convective asymmetries on TC intensity change, and understanding the dynamics of hurricane spin down over the open ocean. The following pages summarize pertinent milestones in each area.

ASSESSING THE BALANCE APPROXIMATION IN TC'S: MOTIVATION AND APPROACH

Although the traditional balance approximation is widely used to extract the asymmetric geopotential height field from the horizontal wind fields in both observational and theoretical hurricane work, the basis for such an approximation in hurricane flows has received little scrutiny. The work described below derives a mathematical criterion under which the traditional balance approximation is formally valid and provides an alternative method for deducing the asymmetric height field from the horizontal winds when the balance approximation breaks down.

Work Completed, Results And Impact

In Montgomery and Franklin (1998) the validity of the traditional balance approximation for the asymmetric flow above the boundary layer in hurricanes is examined. Scaling considerations of the divergence equation show that the validity of the balance approximation hinges on the smallness of the nondimensional product $(\delta_n^{'}/\zeta_n^{'})\times(n\bar{v}/\bar{\eta}r)$. The first term represents the ratio of asymmetric horizontal divergence to asymmetric vertical vorticity for azimuthal wavenumber *n*, while the second term represents a Rossby number based upon the azimuthal mean tangential wind and absolute vertical vorticity of the hurricane vortex. Wind observations of Hurricane Gloria (1985) indicate that this product is not at all small in the near-vortex region (several hundred kilometers beyond the radius of maximum tangential winds) where asymmetric convergence forced by surface friction and cumulus convection is typically large. Although the Gloria observations represent only a single case, there are dynamical reasons to expect this product to be $O(1)$ just above the hurricane boundary layer in steadily translating hurricanes. The meteorological relevance of these results to the problem of balance dynamics in hurricanes is discussed further in Montgomery and Franklin (1998).

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CONVECTIVE ASYMMETRIES IN TC'S: MOTIVATION AND APPROACH

A new mechanism of vortex intensification by convectively forced vortex Rossby waves was proposed by Montgomery and Kallenbach (1997, henceforth MK). The thrust of this work is to further explore the Rossby wave intensification mechanism in hurricane-strength vortices. Here we use both a barotropic shallow-water model and a three-dimensional asymmetric balance (AB) model where convection is parameterized by its estimated net effect on the dry potential vorticity (PV) field.

Work Completed, Results and Impact

The revised version of the paper *Vortex Rossby-waves and their influence on hurricane intensification in a barotropic model* (Möller and Montgomery 1998) was extended by including a strong disturbance which axisymmetrized in a circular flow, and in the process was able to intensify the basic state. Side-by-side comparison with some experiments from a primitive equation model shows good agreement for both weak and strong asymmetric disturbances. An explanation was also given as to why the results of the AB model are similar to the PE model, given that the naive scaling of the squared local Rossby number (a measurement of accuracy) implies large inaccuracies for wavenumbers > 1.

The work of Möller and Montgomery (1998) has been extended to three dimensions. The model is based on the asymmetric balance theory of Shapiro and Montgomery (1993). Möller and Jones (1998) used this theory in a diagnosis of three-dimensional model results. Here we use a fully nonlinear prognostic approach to examine the effect of convectively induced disturbances on the three-dimensional evolution of a hurricane-like vortex. This investigation generalizes that of Montgomery and Enagonio (1998, henceforth ME), who studied tropical cyclogenesis using a forced quasigeostrophic balance model. As gravity waves are excluded in this formulation we are able to focus exclusively on the dynamics of vortex Rossby waves and their interaction with the mean vortex.

An initially barotropic or midlevel tropical storm is initialized with a single-cluster PV anomaly (negative at upper levels, positive at lower levels). The symmetrizing PV anomaly induces changes in the primary circulation analogous to those in the barotropic experiments; the changes are strongest at the top and bottom of the domain. In addition, the baroclinic disturbance induces a secondary circulation that tends to counteracts the changes in the primary circulation. Depending on the strength of the cluster, the upper-level anticyclonic PV anomaly is expelled outward (stronger anomaly), which complements the cyclogenesis results of ME, or is symmetrized (weaker anomaly) similar to the lower-level positive PV anomaly. Similar to ME, we simulate the ongoing process of convection by adding double--cluster PV anomalies to the PV fields every hour (so-called "pulsing"). The tropical storm intensifies depending on the location, extent and magnitude of the anomaly.

Vortex Rossby waves can propagate not only radially but also vertically. For purely linear waves the local dispersion relation generalizes the barotropic dispersion relation of MK (their section 3b) and includes the vertical structure of the disturbance. The model is initialized with a barotropic tropical storm with a radius of maximum wind (RMW) at 145 km, where monochromatic azimuthal wavenumbers 1-3 are superimposed. The distribution of the PV anomaly is such that the maximum is at lower levels at a radius of 170 km and goes to zero in the middle of the vortex. The linear and nonlinear results are very similar, which is not surprising as the disturbance is weak and so the nonlinear interactions have a small contribution. Figure 1 shows a radius--height distribution of the PV asymmetry amplitude initially (a) for all wavenumbers and of the azimuthal wavenumber 1 (b), 2 (c), and 3 (d) after 5 hours. Consistent with the vertical group velocity for a disturbance not too radially or

azimuthally confined the asymmetries propagate faster upward the lower the azimuthal wavenumber n. While the vortex Rossby waves propagate they transport energy, under which some scenarios could potentially impact hurricane intensity. Preliminary results indicate that the azimuthally averaged tangential velocity decreases inside and increases outside the RMW at lower levels as in the barotropic case. At the upper levels, however, the results are reversed. These scientific results are being written up in a formal publication.

Although the AB theory (Shapiro and Montgomery 1993) has been successfully used in linear and nonlinear shallow water models (Montgomery and Kallenbach 1997; Montgomery, Möller and Nicklas 1998; Möller and Montgomery 1998), prognostic and diagnostic nonlinear three-dimensional models (Möller and Jones 1998; Möller and Montgomery 1998), it is necessary to compare the well-established balance equations, the AB theory, and the primitive equations. First results indicate that although the disturbances decay more rapidly in the AB formulation, the radial wave propagation is similar to that in the BE model. An evaluation will be made as to which model results are closer to the primitive equations. Vortex axisymmetrization experiments in a linear barotropic context will allow us to diagnose under what circumstances which model better conserves energy or PV, and compare the stagnation radii, PV asymmetry amplitudes, etc. for the different models. These results will be written up in a formal publication as well.

SWIRLING BOUNDARY LAYERS: MOTIVATION AND APPROACH

As a foundation for ongoing work examining the life cycle of secondary eyewalls in hurricanes we are continuing our study of the hurricane spin-down problem subject to a quadratic drag law in the surface layer.

Work Completed, Results and Impact

The time-dependent theory of Eliassen and Lystad (1997) serves as a useful basis for the numerical experiments presented. The theory is being tested with the assistance of an axisymmetric Navier-Stokes numerical model. Previous work by Yang (1997) suggested a large discrepancy in the half-life time and other aspects of the flow for tropical storm and hurricane strength vortices. However, this disparity has been traced to an error in Yang's numerical model. Upon correcting the numerical model our new results yield half-life times comparable to Eliassen and Lystad's predictions. In short, Eliassen and Lystad's predictions are confirmed for tropical depression, storm, and hurricane strength vortices. The local spin up of vertical vorticity and tangential winds near the surface reported by Yang (1997) is still observed during the spin-down process in the revised models. The source of the spin-up is due to the stretching (convergence) term in the vertical vorticity equation.

Transitions

During FY 1999 it is anticipated that the investigations of three-dimensional vortex axisymmetrization and hurricane spin down will be written up for formal publication. The vortex intensity change accompanying the three-dimensional breakdown of the hurricane's eyewall will also be investigated. We will also apply our theoretical results to help diagnose hurricane intensity change as predicted by the "full physics" Geophysical Fluid Dynamics Laboratory hurricane model. The results of this research will be used to better predict TC intensity change events, which are currently forecast by operational models with little or no skill.

IN-HOUSE/OUT-OF-HOUSE RATIO

All work was performed "out-of-house" in an academic setting.

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Möller, J. D., and M. T. Montgomery, 1998: Hurricane intensification via Vortex Rossby--waves. Preprints, AMS Annual Meeting, Symposium on Tropical Cyclone Intensity Change, Phoenix, Arizona, 11-16 January.

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Montgomery, M. T., 1998: Tropical cyclogenesis and development via convectively forced vortex Rossby waves. Advanced Study Program; Symposium on Hurricanes at Landfall; NCAR, Boulder, Colorado, 14 July .

Montgomery, M. T., 1998: Vortex Intensification by convectively forced vortex Rossby waves. 78th AMS Annual Meeting, Symposium on Tropical Cyclone Intensity Change, Phoenix, Arizona, 11-16 January.

Möller, J. D., and M. T. Montgomery, 1998: Hurricane intensification via Vortex Rossby--waves. AMS Annual Meeting, Symposium on Tropical Cyclone Intensity Change, Phoenix, Arizona, 11-16 January.

Workshop participant during FY-1998:

Fourth WMO/ICSU International Workshop on Tropical Cyclones (IWTC-IV) in Haikou, Hainan Province, China.